An Infrared Solution to a National Priority NASA Ice Detection and Measurement Problem

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ABSTRACT

NASA has a serious problem with ice that forms on the cryogenic-filled Space Shuttle External Tank (ET) that could endanger the crew and vehicle. This problem has defied resolution in the past. To find a solution, a cooperative agreement was developed between NASA-Kennedy Space Center (KSC) and the U.S. Army Tank-automotive and Armaments Research, Development & Engineering Center (TARDEC). This paper describes the need, initial investigation, solution methodology, and some results for a mobile near-infrared (IR) ice detection and measurement system developed by MDA of Canada and jointly tested by the U.S. Army TARDEC and NASA. Performance results achieved demonstrate that the pre-launch inspection system has the potential to become a critical tool in addressing NASA's ice problem.

Keywords: Ice detection; ice thickness, infrared, space shuttle

1. INTRODUCTION

The formation of ice (and frost) is a common occurrence on the Space Transportation System (STS), external tank (ET) Spray-on Foam Insulation (SOFI). The reason being that in Florida's humid and sometime cold weather, frost and ice are formed because the ET contains large quantities of cryogens–in this case liquid hydrogen (LH2) and liquid oxygen (LO2). Ice is a critical safety concern because of the possibility of it being liberated from the ET during liftoff and

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vehicle ascent. Falling ice could strike and possibly damage the orbiter crew compartment windows, Reinforced Carbon-Carbon (RCC) panels on the leading edge of the Orbiter's wings, or its thermal protection tiles, thus placing the crew and vehicle at risk.

NASA-KSC's initial desires and requirements were that an ice detection and measurement system be developed that would be capable of: differentiating ice from water, remotely detecting and measuring ice with a thickness of 1/16 in. thick (0.0625 in.) or more, be portable and be safe for use in the launch pad environment. The 1/16 inch thickness requirement is a Launch Commit Criteria (LCC) limit for safe vehicle ascent. Therefore, any ice detection and measurement system should not significantly underestimate.

The system was to be portable for use by the NASA-KSC ice and debris inspection team on launch pad access walkways and platforms during cryogenic tanking tests and T-3 hour pre-launch inspections. As a result of launch pad planned use, it was also required that the system meet launch complex safety requirements (e.g., be explosion proof and within EMI/EMC limits).

NASA and TARDEC directors signed a collaborative research agreement in 2004 and members of TARDEC's Visual Perception Lab (VPL) performed a technology search and evaluation of potential electro-optical systems capable of detecting the presence and determining the thickness of ice on STS ET SOFI. Previous research by VPL investigators, following NASA inquiries, indicated that it might be possible to detect and image ice-covered areas with an infrared camera. In addition it was realized that methods were needed to detect clear ice (invisible to the naked eye), and to discriminate between ice and water on ET SOFI surfaces.

A technology search initiated by the VPL team resulted in the identification of three electro-optical systems as candidates for further investigation. VPL comparison of these systems, testing, and analyses was the subject of a report submitted to NASA-KSC in June 2004[1]. VPL investigators and NASA engineers agreed that a system developed by MacDonald, Dettwiler and Associates Ltd. (MDA) of Canada offered the greatest potential to support cryogenic tanking tests and T-3 hour ice debris team inspections on the launch pad prior to STS launches[1].

Because of initial favorable test results and the potential for a possible solution to NASA's ET ice assessment problems, system requirements and specifications were developed, and a contract was let to MDA by TARDEC for the purchase (with NASA provided funds) of a proof-of-concept ice detection and measurement system. The MDA system, referred to as the Ice Camera in this paper, was calibrated for SOFI surfaces, and delivered to the TARDEC VPL for independent testing and evaluation.

2. SOLUTION METHODOLOGY

The TARDEC-VPL team performed various tests to determine the effectiveness of the system to detect the presence and to estimate the thickness of ice on ET SOFI test samples provided by NASA-KSC. Testing of the Ice Camera proof-of-concept system at TARDEC confirmed the potential for its application to ET inspection. The system was found to be able to differentiate between water and ice and to provide estimates of the ice thickness, but it exhibited noise in ice thickness readings, and required better calibration[2]. Regardless, this system was a breakthrough in remote ice detection and measurement. NASA decided that an improved system would contribute to NASA's ice detection and measurement needs and add a valuable tool to their toolbox of methods and visual inspection capabilities and experience. The improved system was to be further evaluated during Shuttle pre-launch ET inspections.

2.1 Description and Physical Principle of the MDA Ice Camera

The Ice Camera (shown in Fig. 1) uses an infrared strobe, a focal plane sensor array and filter wheel to collect successive images over a number of sub-bands, and then processes the images to determine whether or not ice is present and to compute ice thickness. The infrared strobe is low power and is used to illuminate a surface (in this case ET SOFI) on which there may be ice. The system which includes a visual and IR camera, a strobe, a video tape recorder and power supplies, is housed in N_2 purged enclosures which are mounted on a two-wheeled portable cart. The inspection cart with camera and strobe mounted on top is shown in Fig. 1.

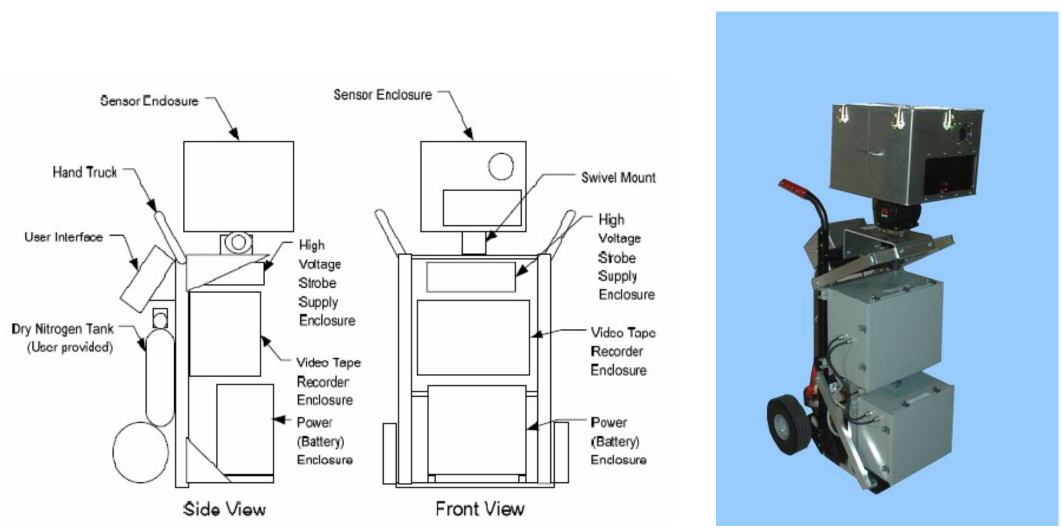

Fig 1: Ice Camera ET Inspection System

Measured ice thickness ranges are color-coded for display on the system monitor. They are: 0-0.020 in. grey, 0.021-0.050 in. green, 0.051-0.060 in. yellow, 0.061-0.070 in. red, 0.071-0.250 in. blue, and 0.251-0.500 in. magenta. These color indications help the operator interpret quantitatively the information and measured ice thicknesses displayed.

The Ice Camera operates on the physical principle discovered [3,4] that there is a specific wavelength band over which the near infrared reflectance and absorption spectra of ice and water are significantly different. Referring to Fig. 2, as light is incident on a thin dielectric (e.g. ice), a fraction of the light is reflected at the air/dielectric interface, and the rest of the light is transmitted through the dielectric. The transmitted fraction propagates through the dielectric until it reflects off the substrate. The light reflected off the substrate returns through the dielectric until it reaches the dielectric/air interface, where it is again partially reflected into the dielectric and the air. Some absorption of the light occurs as it travels through the dielectric, and this is what discriminates between ice and water. The internal reflection continues until all the light is absorbed completely by the dielectric.[3,4]

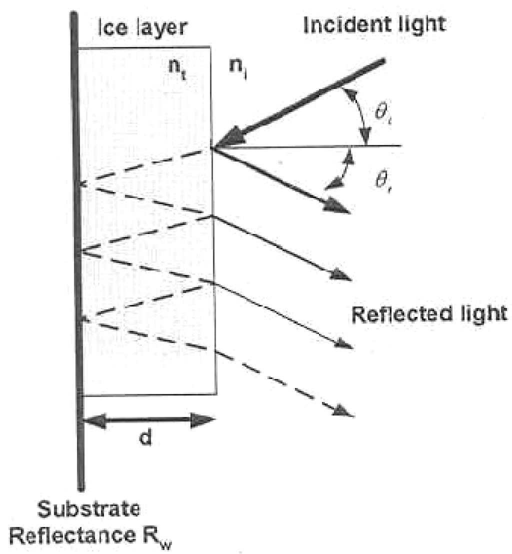

Fig. 2: Reflection of light from a thin ice layer

For a dielectric of thickness *d*, the effective reflectance, $R_e(\lambda,\theta_i)$, of the dielectric layer is given by:

$$R_e(\lambda,\theta_i) = R(\lambda,\theta_i) + \left[\frac{R_w(\lambda)\left(1-R(\lambda,\theta_i)\right)^2 e^{-2\alpha(\lambda)d}}{1-\left(R_w(\lambda)R(\lambda,\theta_i)\right)^2 e^{-2\alpha(\lambda)d}}\right] \tag{1}$$

where,

$R_e(\lambda,\theta_i)$ is the effective reflectance
$R(\lambda,\theta)$ is the dielectric spectral reflectance
$a(\lambda)$ is the spectral absorptivity
$R_w(\lambda)$ is the substrate spectral reflectance.

Fig. 3 shows the computed effective reflectance as a function of wavelength for 0.50 mm (0.02in.) ice and water layers with light incident normal to the surface.

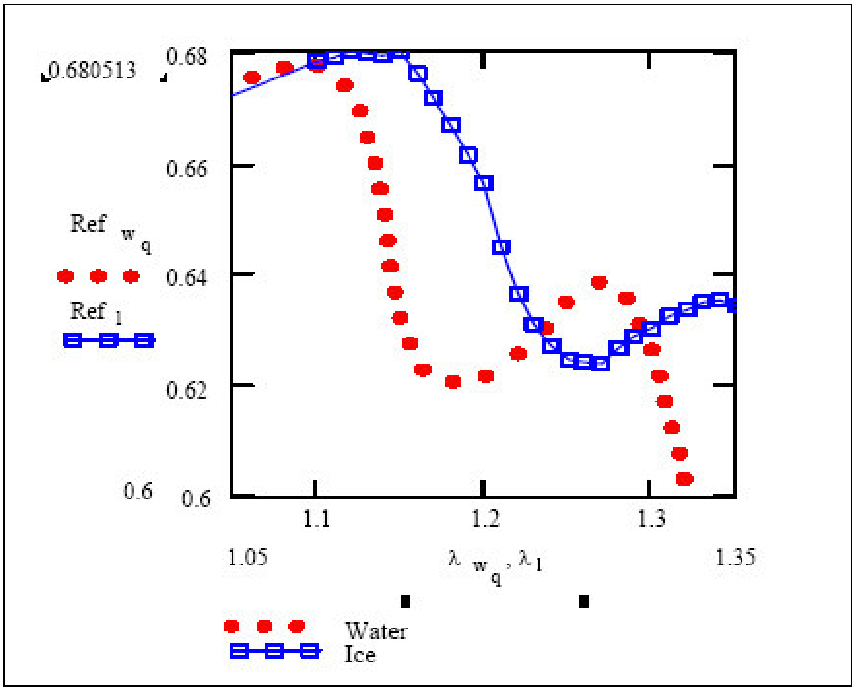

Fig. 3: Computed spectral reflectance of ice and water versus wavelength[3]

It is clear from Fig. 3 that the infrared reflectance of water and ice is different. This difference can be measured by using specific sub-bands within the near IR region of 1.1-1.4 microns, and calculating the spectral contrast defined as,

$$C = \left[\frac{R_l - R_u}{R_l + R_u} \right] \tag{2}$$

where *l*, and *u* are the lower and upper bands respectively in Equation 2. Measurement of the reflected energy and the computation of the spectral contrast allows for the detection of ice on a surface and the estimation of the thickness d, of the ice on that surface. Using the spectral contrast, the Ice Camera can be calibrated to provide estimates of ice or water layer thickness.

The Ice Camera measures ice thickness indirectly, because the camera remotely detects the quantity of ice from the returned signal. From this signal, which is proportional to mass, ice thickness is determined internally within the Ice Camera system. The ice thickness to spectral contrast calibration therefore is dependent on the density of the ice used during the calibration. Ice with densities greater than ice density used during calibration will have a greater thickness reading because there is more ice per unit volume. Conversely, lower density ice or frost will appear to be thinner than actuality. The accuracy of the ice thickness relation is also dependent on the viewing angle to the ice. As the viewing angle moves away from the surface perpendicular, the spectral contrast decreases for a constant thickness of ice. The effect becomes significant as the view angle is greater than 55 degrees from the surface perpendicular.

2.2 Test Location

The Ice Camera was tested at an indoor test range located at the Selfridge Air National Guard Base (SANG) in MI. Fig. 4 is a photograph of the test setup, showing the relationship between the MDA unit in the foreground and the inspected cryo test panel in the background. Fig. 5 shows the cryo panel, ice covered SOFI sample with grid references, and supporting test equipment.

Fig. 4: Test set-up in hanger

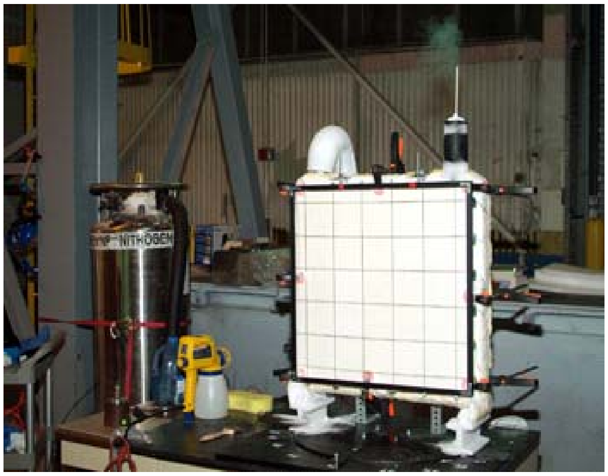

Fig. 5: Ice-covered SOFI test panel

The SANG facility could be used for a range of environmental conditions (e.g., 35-86 degrees F and 30-75% relative humidity) but the unregulated ambient environmental conditions complicated consistent ice formation and stability throughout the many repetitive cycles of the test.

A Kaman eddy current thickness measurement tool (shown in Fig. 6) with an uncertainty of ±0.001 inch was the standard for measuring ice layer thicknesses. The Kaman eddy current device measures the thickness of an non-metallic material, in this case ice on SOFI, above a metal surface in which eddy currents are induced. A three-inch diameter Kaman sensor was used and provided thickness measurements averaged over its diameter. A SOFI baseline thickness was determined using the Kaman sensor and its digital readout after liquid cryogen was present in the test Dewar, but prior to the presence of ice. After ice was formed, the Kaman was again placed on top of the test ice and a new measurement made. Ice thickness was then determined from the difference of the two readings and the process was repeated. The density of the ice layers was also required to be representative of actual launch site ET SOFI ice. The density of the ice layers wase determined by subtracting the weight of the clean SOFI panel-(weighed at the beginning of a test run)- from the weight of the ice covered SOFI panel after the Kaman measurements were made of a new layer of developed ice. Measurements were made in the English system of units to conform to NASA's usage.

Fig. 6: Kaman sensor being used to measure the average ice thickness over a grid of locations

Fig. 6 above shows the Kaman unit being used to measure ice thickness on an ice-covered SOFI test sample. A reference grid was used to repeatedly measure the ice in each region of the surface.

The general test measurement sequence was the following, Kaman measurements for specific target areas followed by Ice Camera readings, followed by additional Kaman measurements to insure accuracy. For the purpose of testing the Ice Camera accuracy, the Kaman was used as the *measurement* standard, and the Ice Camera was used for *readings* to be used for accuracy comparison.

3. RESULTS

Experimental data were collected with the Ice Camera at various distances from the SOFI panel, viewing angles, ice densities, and illumination levels. Representative summary data and analyses are as follows for multiple test periods.

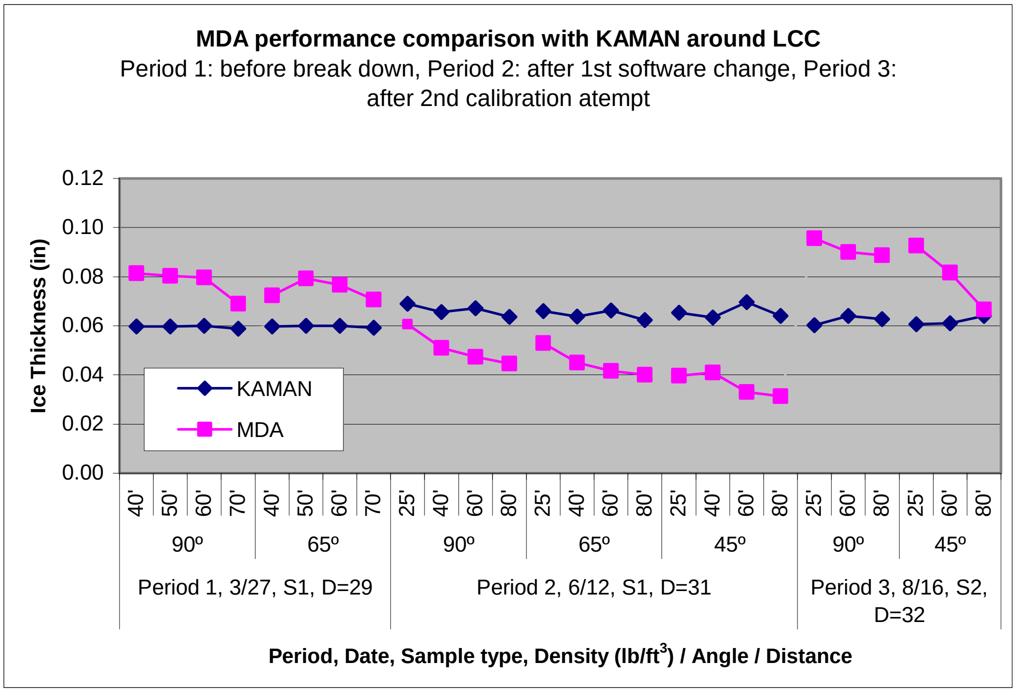

Fig. 7 MDA and Kaman comparison around LCC following a calibration attempt

The chart shown above in Fig. 7 is a consolidation of data from three test periods before and after ice thickness determination. The objective of this combined data is to determine the accuracy of the Ice Camera around the LCC ice thickness of 0.0625 in. The test densities were 29, 31 and 32 lb/ft^3 which are within the nominal KSC densities of 30 to 40 lb/ft^3, and the viewing angles are restricted to 90, 65, and 45 degrees. Represented is a full range of viewing distances from 25 to 80 ft. between the ice test panel and sensor.

The data show that throughout the three periods, the Kaman readings were consistently within ±0.005 inches of the LCC, suggesting ice preparation method and hangar environmental conditions were fairly consistent. The Ice Camera thickness results show a consistent thickness estimate but with a bias that varies with each calibration attempt. The bias in the first two calibrations was <0.02 in. and the last calibration introduced a larger positive bias of approximately 0.038 in. The results suggest the importance of the system thickness calibration. The data show that usually, the ice thickness estimates decrease as the angle to the surface becomes shallower. For the more accurate calibrations, the thickness estimates are also consistent within 0.01 in. over the 25 to 80 ft range.

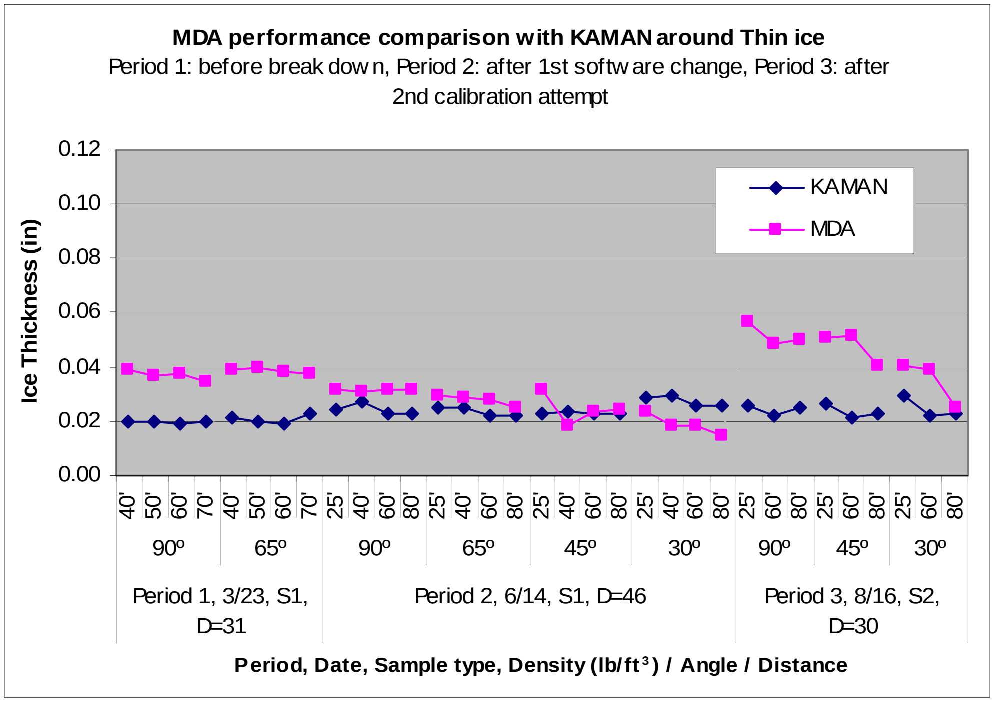

Fig. 8: MDA versus KAMAN comparison for thin ice following calibration attempt

Fig. 8 above shows the results for ice layers thinner than LCC ice, around 0.02 to 0.03 in. Two of the test densities are within the nominal KSC densities of 30 to 40 lb/ft^3, namely 31 and 30 lb/ft^3 respectively, but the third is for a density of 46 lb/ft^3. For this group of data, viewing angles are 90, 65, 45, and 30 degrees, and a full range of viewing distances from 25 to 80 ft.

Again the Kaman unit shows that the ice preparation technique and the procedural use of the Kaman measurement were consistent. For thin ice around 0.020 in., the viewing angle appears to be less important and there is good agreement between the Kaman and Ice Camera, except in the third period after the latest calibration. The MDA system during the second period agreed within ±0.005 in. of ice thickness even for high-density ice of 46 lb/ft^3 except at 30 degrees where Ice Camera readings are less than the Kaman measurements. The first period shows a greater difference but the Ice Camera operation is linear over distance and angle. This data indicates that with a good calibration, the Ice Camera produces consistent measurements over distances of 25 to 80 ft.

Fig. 9 below shows more recent Ice Camera calibration attempts. For this testing and data collection, a recalibrated Ice Camera contrast-to-thickness algorithm was provided by MDA determined from earlier collected data. Using a distance of 50ft. and 80 degree panel orientation, precalibration and post calibration data was collected. The chart in Fig. 9 shows the computed thickness from the Ice Camera is in very good agreement with the Kaman measurements. Hence, through testing, the Ice Camera can be calibrated.

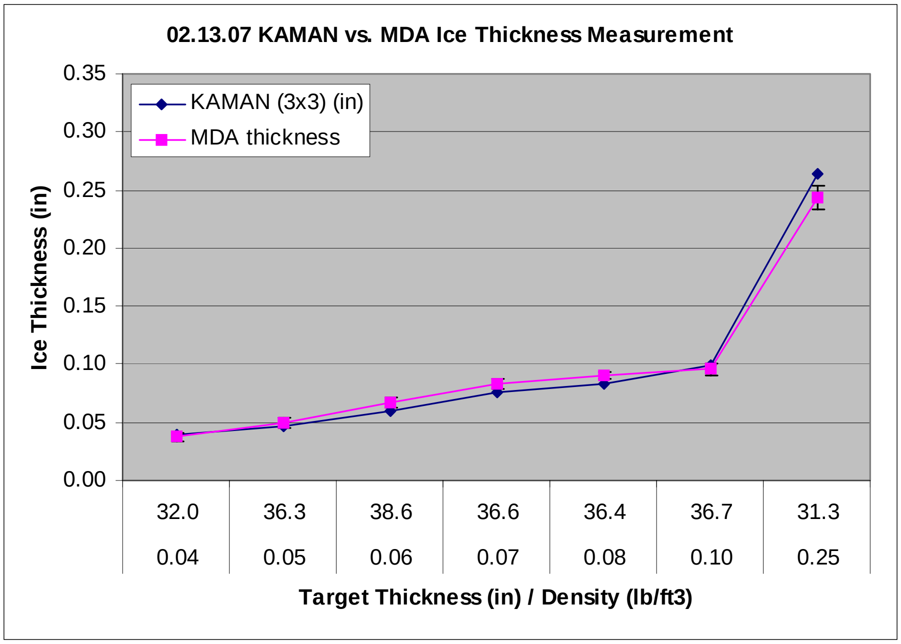

Fig. 9: Feb 07 Ice Camera versus Kaman for various ice thicknesses

3.1 Application of the Ice Camera for STS-116 Pre-launch Inspection

During the T-3 hour inspection for mission STS-116 in December 2006, the Ice Camera was taken to the launch pad by the ice and debris inspection team and used to image the ET. Various views of the Ice Camera in use are shown below. Fig. 10 shows an Ice and Debris team member using the Ice Camera to make a measurement at the Fixed Service Structure (FSS) 215-foot level crossover to the Rotating Service Structure (RSS). This location provides the view given in Fig. 11 of approximately one-half of the LO2 tank acreage that is designated as a "no ice zone." The view is complimented by the view from the RSS roof location that sees the entire “no-ice” zone as shown in the (b) image of Fig. 11. The picture labeled Fig. 12 shows the Hydrogen Tank gaseous vent umbilical disconnect within the Intertank portion of the External Tank as viewed from the FSS.

Fig. 10: Ice Camera in use for STS-116 pre-launch inspection

Fig. 11: Visible (left) and Ice Camera (right) infrared images of Shuttle External Tank during STS-116 pre-launch inspection. No ice was detected or is present. The Ice Camera range was approximately 80 ft.

Fig. 12: Visible (left) and Ice Camera (right) infrared images of Shuttle External Tank GH_2 umbilical connection. Thin ice is shown as a green overlay.

4. DISCUSSION

The Ice Camera has demonstrated the capability to remotely detect and measure the thickness of 0.02 to 0.25 inch ice layers on the Space Shuttle External Tank SOFI. In general, the accuracy is within 0.02 inches for near normal viewing angles and ice densities between 30 and 40 lbs/ft^3. However, the accuracy of the ice thickness measurements depends on several variables including the quality of the ice thickness calibration function, the density of the ice layer, the viewing angle of the camera to the surface, and Ice Camera measurement noise. The interactions of these independent variables can complicate the calibration.

The quality of the ice thickness calibration is determined foremost by the uniformity of the test ice layer thickness and density built on the SOFI test panel. Meticulous care must be taken to ensure that the ice is developed evenly over the panel and that the density remains within the range of representative ice densities. The second factor determining the quality of the calibration is careful measurement of the physical ice thickness over the SOFI using the Kaman eddy current sensor. A protective, insulative stand-off material between the sensor and the ice must be used so as not to melt the ice. The density of the ice must also be measured after each ice layer is built since the density changes with thickness.

The viewing angle to the surface affects the ice thickness measured by the Ice Camera so during calibration the view angle to the surface is fixed. In addition, the Ice Camera noise contributes to experimental uncertainty which is mitigated by averaging the data for each ice layer. Improving the quality of the calibration reduced bias errors of 0.02-0.03 inches to less than 0.008 inches.

The Ice Camera was successfully applied to the inspection of the ET on STS-116. The camera did not produce any false alarms and the Ice Camera detected thin ice/frost layers on two umbilical connections that were verified by visual inspection at ranges in excess of 50 feet.

Current testing of the prototype Ice Camera is aimed at determining its ability to detect and measure 1- to 3-inch diameter ice balls formed in ET SOFI breaks. NASA has identified ice ball detection and measurement as an additional requirement for the Ice Camera beyond ET acreage ice measurements. It is planned that the Ice Camera will be used for the STS-117 launch.

The results of ongoing tests will contribute to the development of an improved next-generation operational ice detection and measurement system that meets NASA’s needs and will add a valuable tool to their toolbox of methods and visual inspection capabilities and experience.

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